Terrestrial Planet Finder Coronagraph (TPF-C)
White Paper for the NASA-NSF Exoplanet Task Force

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Abstract

The Terrestrial Planet Finder Coronagraph (*TPF-C*) is a space mission designed to **detect and characterize** Earth-like planets around nearby stars, and to search for signs of life on these planets. It will use spectroscopy to measure fundamental properties including the presence of water or oxygen in the atmosphere, powerful signatures in the search for habitable worlds. In addition to its primary goals of planet detection and characterization, TPF-C will also serve as a powerful general-purpose astrophysics platform performing a wide range of science far surpassing the capabilities of the Hubble Space Telescope. The technologies for carrying out this mission are either in hand or tantalizingly close to fruition. The mission architecture is flexible and can be scaled to match available resources while still achieving the goal of characterizing Earth-like planets. We seek endorsement from the ExoPlanet Task Force for a mid-scale mission in the next decade.

1. Overall Scientific Goals

The scientific goals of the TPF-C mission—to discover and study Earth-sized planets around neighboring stars—are ambitious, exciting and profound, addressing some of the most important questions humankind can ask about its place in the universe. Scientists have found a variety of giant planets, and are poised to find smaller planets, more and more like the Earth. TPF-C will be our first chance not only to detect large numbers of Earth-sized planets nearby, but also to see them directly, measure their colors, study their atmospheres, and look for evidence of life there. These goals make TPF-C a special project in the history of astronomy, one capable of firing human imagination and revolutionizing the way we think about ourselves and the universe.

With over 200 mostly Jupiter-mass or larger planets discovered to date, the next frontier for planet-finding is to look for rocky, terrestrial-type planets around other stars. NASA's upcoming Kepler mission[1] and ESA's CoRoT mission[2] will do this for more than a hundred thousand very distant stars, while the Space Interferometry Mission (SIM PlanetQuest)[3] searches around nearby stars. Both Kepler and SIM have the capability to detect at least a few Earth-size planets if they are common. Ongoing ground-based searches may also reveal Earth-mass planets around very low-mass stars. TPF-C, however, is being designed to search for Earth-sized planets (and smaller) around nearby stars, and more importantly to characterize their composition. These stars span a wide range of masses both smaller and larger than the Sun.

How well TPF-C will be able to characterize the planets it discovers depends on the design of both the telescope and the spectrograph. The baseline design has a wavelength range of 0.5-1.1 μm and a spectral resolving power, $\lambda/\Delta\lambda$, of 70. For an Earth twin (planet and star exactly like our Earth and Sun) seen at 10 pc distance, these capabilities would enable TPF-C to measure absorption bands of water vapor, oxygen, and possibly ozone. The presence of water vapor is an indicator of potential habitability, as liquid water is considered to be a prerequisite for life as we know it. Oxygen and ozone are potential indicators of life itself, because on Earth oxygen is generated by photosynthesis and ozone is generated by sunlight acting upon oxygen. It is conceivable that there are rare planets on which O_2 and O_3 can build up abiotically, but for most planets within the liquid water habitable zone, these gases are considered to be reliable bioindicators. Hence, TPF-C is the first mission with the potential to provide compelling evidence of life on extrasolar planets.

TPF-C can also study giant planets and dust disks — the entire planetary system architecture — at the same time that it looks for Earth-like planets, supporting studies of the potential habitability of any Earth-like planet. If our own Solar System is a guide, planets like Earth are found in planetary systems that include other small rocky planets, e.g., Venus and Mars, along with gas giants like Jupiter and Saturn, and ice giants like Uranus and Neptune. The larger planets are of interest in their own right, but they may also be crucially connected to the habitability of the Earth-like planets. In our own Solar System, for example, Jupiter helps shield Earth from collisions with comets, but also perturbs some asteroids into Earth-crossing orbits. Thus understanding the potential habitability of an Earth-like planet requires study of the entire planetary system architecture.

TPF-C will also study the dust clouds around stars, to learn about the process of planetary formation. Some observations of very young stars will be included, though these stars are not favorable for the terrestrial planet search program. Planetary systems themselves do not occur in isolation around stars. Collisions between small bodies (asteroids) within the system, and vaporization of icy planetesimals (comets) from farther out both create dust that orbits the star along with the planets. This dust reflects starlight, giving rise to the zodiacal light in our own Solar System and to exozodiacal light in other planetary systems. The planets in a given system must be observed against these backgrounds of the "zodi" and the "exozodi." The exozodiacal light in a given system must be measured and subtracted in order to see the planets. However, it is also known that the dust distribution can be perturbed by the gravitational influence of planets; thus the exozodi light may be a powerful tool for finding and studying the planets in a system. For these reasons, the study of exozodiacal dust clouds is an integral part of the TPF-C mission. Mapping out the exozodiacal light can be carried out simultaneously with the search for terrestrial planets.

In addition to its primary goal of characterizing terrestrial planets and the dusty systems that accompany them, TPF-C will make substantial contributions in other areas of general astrophysics. The telescope will be very large, smooth, and stable, and so will exceed the performance of HST in several respects, including collecting area, angular resolution, and point spread function stability. To take advantage of this large telescope, a separate instrument—a wide-field camera—is planned in addition to the coronagraph. This instrument would channel light along a different optical path, and hence could perform its tasks either in parallel with planet-finding activities or by using the telescope in pointed mode. The science that could be performed in parallel includes imaging of distant galaxies, similar to the Hubble Deep Fields but with even greater depth and clarity. Such deep fields could be obtained over periods of one day to several weeks. Pointed observations will yield key constraints on theories of Dark Energy, through precise measurements of the Hubble constant and the distance versus redshift relation. Observations of collections of stars in the Milky-Way and nearby galaxies will probe the "fossil record" of star formation, using stars too faint to detect with HST or JWST.

Further details of the TPF-C science goals can be found in the TPF-C Science and Technology Definition Team (STDT) report.[4]

2. Detecting Earth-like Planets

Earth-like planets orbiting in the habitable zone (HZ) of nearby stars are ~ 10^{-10} times as bright as the stars, at angular separations of ~ 0.1 arcsec. Direct imaging and characterization of these planets requires a substantial collecting aperture, high angular resolution and careful control of the optical wavefront. Extensive mission modeling by groups at JPL, STScI, and GSFC has explored the ability of strawman TPF-C designs to detect these planets around the known, nearby stars. The modeling has been used to set the high-level performance requirements that in turn drive the engineering requirements in the telescope, coronagraph, and their control systems.

The ability to detect planets is characterized by observational completeness, the fraction of possible planets that are detectable.[5,6] Completeness is determined through the simulated observation of an 'orrery' of planets orbiting throughout the habitable zone of each star. These planets are assumed to be spherical Lambertian reflectors with size and albedo identical to the Earth's. The planets in the orrery are considered to be detected when three conditions are met: they are separated by an angle greater than the coronagraph's inner working angle (IWA); they are bright enough to achieve the required signal-to-noise ratio (SNR) in a prescribed amount of time; and, their flux ratio relative to the star is brighter than the limiting delta magnitude, Δmag. Completeness is the fraction of planets detected divided by the total number of planets, and is expressed as a fraction of the habitable zone, e.g. if half the planets are detectable, the completeness is 0.5 HZ. Given the probability η_{earth} of an earth-like planet existing around a star, the total number of detectable planets in a program is the sum of the completeness over all stars times η_{earth}.

Figure 1 shows the total completeness for programs based on several telescope/coronagraph options as well as an external occulter option. The 8 x 3.5 m aperture is assumed to use a band-limited Lyot coronagraph,[7] while the 4 m telescope is shown with both a band-limited coronagraph and a high-throughput Phase Induced Amplitude Apodization[8] (PIAA) coronagraph (both coronagraphs are described below). The points were generated assuming that 1/3 of the 3-yr detection phase is spent searching for planets. The calculation also assumes that the coronagraph limiting sensitivity is Δmag = 25.5, the spectral resolution is R=5, and that the density of the exozodiacal dust is the same as in our solar system. For all cases shown, the number of targets observed is roughly twice the cumulative completeness. For the coronagraphs, many stars are revisited several times during the detection phase.

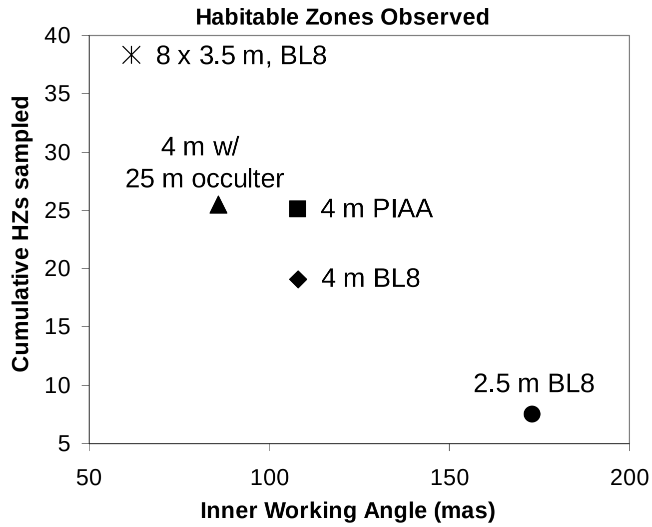

Figure 1. Total number of HZs searched. The number of Earths detected is η_{earth} * cumulative HZs searched. BL8 = Band Limited 8th order mask. PIAA = Phase Induced Amplitude Apodization. The 8 m design assumes IWA = 4 λ/D. The 4 m and 2.5 m designs assume IWA = 3.5 λ/D.

The modeling tools were also used to evaluate the performance of an external occulter combined with a 4-m telescope. Assuming 6-day slew time between stars, and a deeper sensitivity Δmag = 26, than an internal coronagraph, the 25 m diameter occulter plus 4-m telescope would have an observational completeness of 25 HZ, the same as a single 4-m telescope using a PIAA coronagraph, and 20% higher than the baseline BL8 coronagraph.

Figure 1 shows that the mission completeness is a strong function of the IWA. A 4-m telescope needs IWA ~ 100 mas to sample 20-25 HZs while observing 40 – 50 stars. Many are visited multiple times. This requirement drives the system to achieve high contrast as close as the third Airy ring, at about 3.5 λ/D with the wavelength λ = 600 nm and telescope diameter D = 4 m. It is worth noting that PIAA is significantly faster than BL8 and achieves the same completeness in about ¼ of the time (see Navigator Program white paper). If PIAA can be made to work at 2 λ/D, as is theoretically possible, then a 4-m telescope achieves higher completeness than the 8 x 3.5 m baseline design.

The detection scenario, with R=5, naturally lends itself to spectrophotometric characterization. Higher resolution, R=70, is carried out using an integral field unit spectrometer, a preliminary design of which was included in the TPF-C Instrument Concept Studies completed in 2006 and described in the STDT report.[4]

Mission studies are still in their early stages. While observational completeness is well understood, work continues in the development of a design reference mission that minimizes false detections, determines orbital parameters, and ultimately characterizes the maximum number of discovered planets.

3. Mission Concept

A coronographic telescope that can achieve 10^{-10} contrast at the third Airy ring has the following opto-mechanical characteristics. First, the telescope has a monolithic primary mirror and is used off-axis so that there are no obstructions to the beam. Segmented mirrors scatter too much light, have low throughput, and require picometer control between segments. Second, the telescope and coronagraph are extremely stable for timescales up to several hours. This requires unprecedented thermal control and vibration isolation. Third, the coronagraph efficiently removes diffracted starlight without removing planet light. This rules out Gaussian-mask coronagraphs but fortunately there are several promising technologies that are expected to be effective at controlling diffraction to the required levels. Fourth, a set of deformable mirrors (DMs) and an associated wavefront sensing system are used to control the wavefront. At least two DMs are needed for broad-band control of phase and amplitude imperfections in the system.

Note that a perfect primary mirror is not a requirement. The existing state-of-the-art in large mirror fabrication already produces mirrors with power spectral densities of surface errors that meet TPF-C requirements. As long as the imperfections are within the capture range of the DMs, they can assume a shape that cancels the scatter from the primary mirror and produces a broad-band dark hole. The same is true for the secondary mirror, which has been shown in studies to have requirements substantially relaxed compared to the state-of-the-art.

3.1 Flight Baseline 1 (FB1)

In the 2002 – 2005 time frame, JPL led a joint study with GSFC culminating in a design called FB1. This is a deployed off-axis Richey-Chrétien telescope with an 8x3.5 m elliptical shaped primary mirror. The mirror is a ULE face sheet fused to lightweight ULE honeycomb core cells and mounted on 3 rigid supports. The mirror is elliptical in shape so that it can be packaged into an existing Delta IV launch fairing. The 8 m dimension was chosen to enable operation at 4 λ/D, as has been demonstrated in HCIT, while at the same time meeting the science requirements set forth by the STDT. FB1 is at either L2 or in an earth-trailing orbit, and it is surrounded by a multi-layer V-groove sunshade that keeps solar energy from perturbing the optics. The FB1 optics are heated to ~273 K so that they operate at the manufactured temperature to minimize deformation. It has HST-like pointing requirements and an active isolation system between the spacecraft and the science payload. FB1 employs a coarse (large-stroke) DM at an image of the primary mirror to compensate for gravity release of the mirror on orbit.

The FB1 observational scenario is based on a 'set and forget' wavefront control approach. After acquiring a target star, the wavefront is controlled to a contrast of 10^{-10}. The science observation begins and then continues for a time sufficient to obtain a photometric SNR of ~ 5 at Δmag = 25.5 (planet minus star). The observatory then rolls 30^{o} about the line of sight and begins to integrate again. Only the pointing control system is active; the DMs are not commanded. Planets are detected in the roll-differenced images. This scenario requires the optics to remain stable during long integrations and it places severe requirements on the thermal and jitter control systems. The alternative to roll-subtraction, however, is to perform unbiased wavefront estimation at a contrast of 10^{-11}; models have yet to show that this is a realistic approach, but it may be a path to relaxing stringent requirements.

During this work an extensive error budget was developed.[9] The error budget identified the major contributors to loss of contrast, namely thermal mirror deformation, lateral beam walk due to pointing errors, and coronagraph mask manufacturing tolerances. The FB1 modeling work has shown that the thermal and dynamic perturbations during operation can be controlled to ensure that the image-plane contrast meets requirements. The sunshade isolates the telescope and payload adequately. Active vibration control easily isolates the payload from reaction wheel vibrations. Vibrations from mechanisms in the instruments and starlight suppression system have yet to be included, but selective damping seems feasible and promising.

An important aspect of this work is that commercial thermal and dynamic analysis software have limitations that are becoming well understood, and the FB1 team implemented patches where appropriate to produce credible results. For longer term production mode use, better integrated modeling tools are being developed. These will provide parallel code architectures for much improved analysis cycle time, efficient inter-operability between the multi-physics analyses (thermal, structural, dynamics, controls and optics) and numerical algorithms required for high accuracy solutions.

FB1 serves as a proof-of-concept for TPF-C and as a foundation for future designs.. There were no major show-stoppers identified and the observatory performance meets the planet detection requirements. A more detailed account of the FB1 design and performance are described in the TPF-C STDT report.[4]

3.2 A Mid-Scale TPF-C

While FB1 is designed to meet the STDT requirements, it is highly complex, massive, and, obviously, expensive. It has multiple deployments, including the secondary tower and secondary mirror, and a 12-m high, 16 m wide multi-layer sunshade. The design does not have sufficient mass margin, and launch loads on the primary mirror are an issue. Fabrication of the primary mirror has a lead time of many years, and testing of such a large telescope is extremely complex, probably requiring new facilities. These problems are not insurmountable, but the question remains, can some compromise in science capability lead to a greatly simplified design?

The answer is Yes, a non-deployed 4-m class telescope (Figure 2) can perform a significant terrestrial planet detection and characterization program at a small fraction of the cost, with greatly simplified testing, short lead times, and adequate mass margin. The risk of developing and flying the monolithic PM can be significantly reduced by allocating mass, in our case targeting areal densities of 50 to 100 kg/m^2, which is more than an order of magnitude greater than demonstrated mirror lightweighting. A mid-scale TPF-C mission can carry out a significant general astrophysics program that far-surpasses the capabilities of HST. Brown et al first described a 4-m version of TPF-C.[10]

Figure 1 shows that a 4-m telescope operating at 3.5 λ/D samples 20-25 habitable zones (from 40 – 50 target stars), leading to a detection of 20-25 Earth-like planets assuming $\eta_{earth}=1$. But there is no free lunch; a band limited coronagraph working at 3.5 λ/D is beginning to climb the slippery slope of the central point spread function. It has several times tighter stability and wavefront sensing and control requirements than the FB1 design that is used in the relative foothills of 4 λ/D. Yet this is a reasonable approach given that the smaller, and much stiffer, telescope will naturally be much more stable than its 8-m big brother. Preliminary models show that a 4 m design is expected to meet the performance requirements for detection of Earth-like planets with this more aggressive coronagraph implementation.

We find that for detection of extrasolar terrestrial planets, the smallest practical telescope is ~ 2.5 m in diameter. This has a completeness of < 10 HZs and it faces substantially longer integration times than the 4-m due to its poorer resolution and smaller aperture.

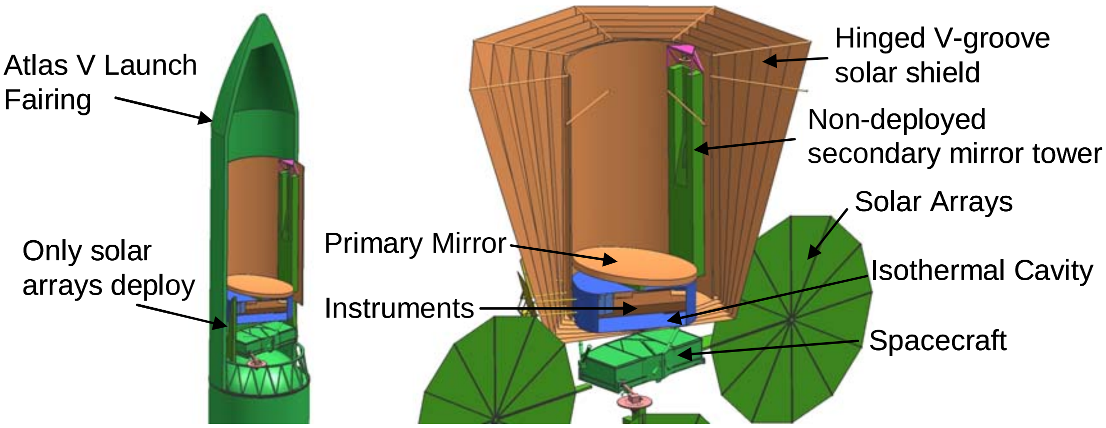

Figure 2. A 3.8 m version of TPF-C shown in its launch configuration and after deployment

4. Suppressing Starlight

The key technical challenges for TPF-C begin with the starlight suppression system (SSS). The baseline mission design SSS carries both a Lyot coronagraph and a shaped pupil coronagraph.[11] The Lyot coronagraph uses a band-limited eighth-order mask (BL8) which like the shaped pupil is very effective at rejecting thermally-induced changes to low-order aberrations in the system. The 8^{th}-order null, in particular, is critical to relaxing the stability requirements to levels achievable with the FB1 thermal and jitter control systems. The SSS carries several masks optimized for discovery and characterization for different stellar classes. However, none of the masks are useful at inner working angles much below $3.5\lambda/D$.

The aforementioned PIAA coronagraph uses a pair of highly aspheric optics and a pair of edge apodizers to create an apodized beam that retains ~ 80% of the light and angular resolution yet concentrates all but a small fraction of the light into a small spot. The overall throughput and image plane resolution are ~ 2x higher than with a band-limited mask. This accounts for the larger observational completeness in Figure 1. PIAA is still in the developmental stage, having achieved in the laboratory contrasts better than 10^{-6}. Plans are in place to test a PIAA system in HCIT in the near future.

The results obtained in JPL's HCIT testbed[12] using band-limited masks are tantalizingly close to meeting TPF-C requirements. The testbed contains almost all the complexity of the TPF-C back-end: a large format (32 x 32 actuators, with 64 x 64 in preparation) deformable mirror (DM), re-imaging optics to provide the Lyot and intermediate image planes, filter wheels, and a CCD camera. The optics are readily available with r.m.s. surface quality of about $\lambda/20$. The high-contrast results are obtained over a region spanning 4-10 λ/D, adequate for most TPF-C stars. While the monochromatic contrast obtained was ~ 6×10^{-10}, the stability of the nulls over time scales of several hours is already good enough (0.1×10^{-10} or 0.1 Earths) to detect Earth-like planets in the habitable zone. Figure 3 shows the experimentally obtained nulled dark hole and residual speckles obtained in monochromatic light and processed with the roll-subtraction method. Superimposed on the speckles is a model planet with flux ratio equivalent to Earth at quadrature. This exciting result, accepted for publication in the journal Nature[13], demonstrates the end-to-end ability to control scattered light to levels sufficient to detect Earth-like planets.

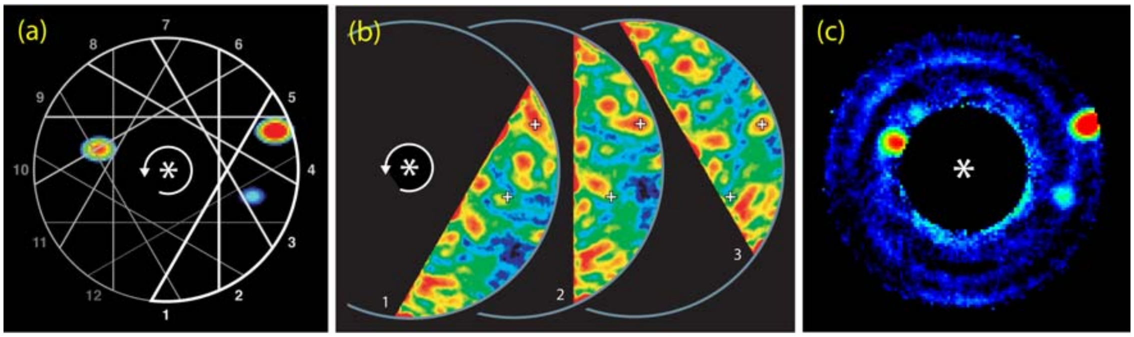

Figure 3. HCIT Laboratory images demonstrate contrast at levels required to detect an Earth-twin. (a) Three planet images are shown on the sky. The planets are copies of the measured star but reduced in intensity by factors of (10, 5, and 1) × 10^{-10}, corresponding to the typical intensities of Jupiter, half-Jupiter, and Earth, respectively. The Earth-twin is at about 4 o'clock, and Jupiter-twin at 2 o'clock. The D-shaped field of view rotates on the sky as the spacecraft is rotated about the line of sight to the star (asterisk). (b) Three sample images at different rotation angles illustrate the observing sequence. Note that the planets (white + signs) are fixed in inertial space, and just barely visible. The rotation sequence continues to fill a full annular field of view. (c) Roll deconvolution is applied to the data, removing the background speckles that rotate with the spacecraft, and keeping the part of the image (planets) fixed in the sky. The planets stand out clearly against the residual background noise, which is the time-varying part of the speckles.

5. Conclusions

When it eventually flies, TPF-C will be one of the most scientifically exciting missions ever launched. A positive indication of extraterrestrial life, or even the detection of a habitable planet similar to Earth, would alter the way in which humans look at themselves and at the universe.

The currently planned funding level for TPF (combined ~ $6M per year for TPF-C and TPF-I through 2012) supports moderate technology development and small architectural and mission studies. This level of funding is insufficient to support detailed engineering studies to follow the highly successful FB1 design effort. Without a serious commitment from NASA, TPF-C will not happen in the foreseeable future.

We seek endorsement from the ExoPlanet Task Force for a mid-scale mission in the next decade. TPF-C is buildable, testable, launchable, and will be a prolific scientific instrument.

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